



EPIC



Extra-Solar Planetary Imaging Coronagraph

Rick Lyon

Navigator Program Forum 2007

PI: Mark Clampin (GSFC)

Deputy PI: Gary Melnick (SAO)

EPIC Team

Rick Lyon (GSFC)

Scott Kenyon, Dimitar Sasselov, Volker Tolls (SAO)

Holland Ford, David Golimowski (JHU)

Larry Petro, George Hartig, William Sparks (STSCI)

Garth Illingworth, Doug Lin (UC Obs/Lick Obs)

Sara Seager, Alycia Weinberger (Carnegie/DTM)

Martin Harwit (Cornell U)

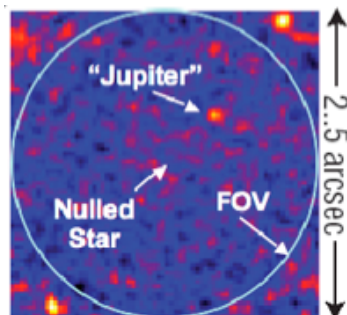
Mark Marley (NASA/Ames)

Jean Schneider (Paris Obs)

Mike Shao, Marty Levine (JPL)

Jian Ge (U of FLA)

Bob Woodruff (LMCO)

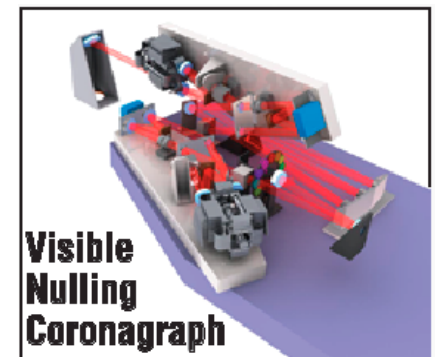


Post-processed
(matched filter)

Epic: "long series of events characterized by struggle"

Epicurus (342 - 270 B.C.) 'universe must be infinite and contain an infinity of worlds.'

EPIC - Extra-Solar Planetary Imaging Coronagraph





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Overview

Proposed as NASA/Discovery Mission (2006)



Proposed as NASA/Discovery mission

• Science

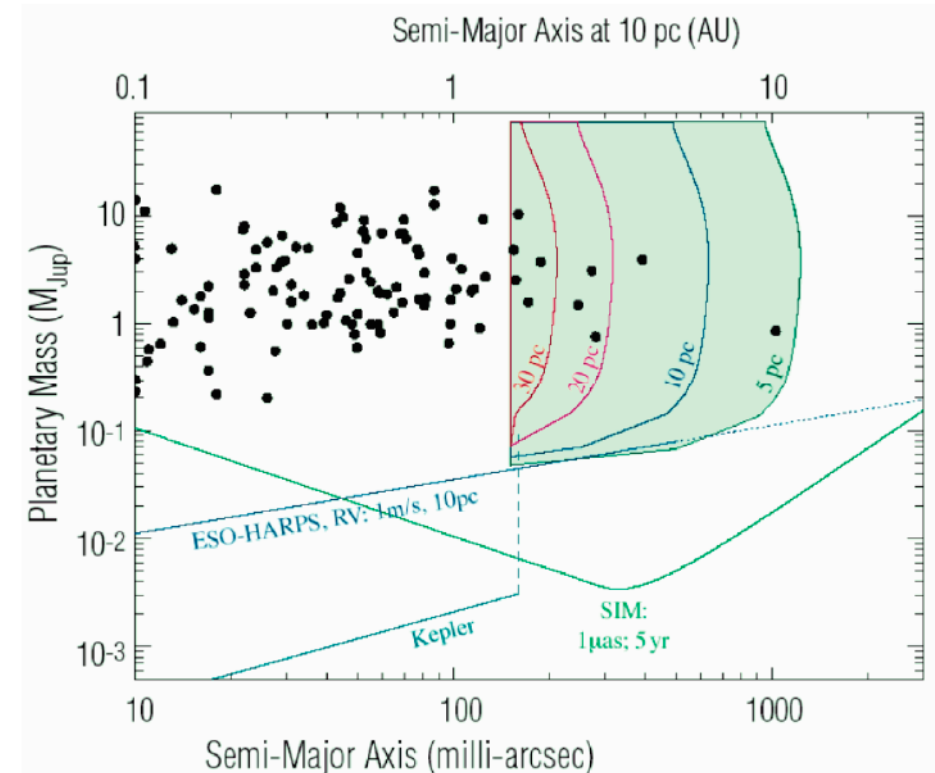
- Jovian planets $\sim 1 - 100 M_{\text{Jup}}$
- Detect & Characterize Jovian planets
- IWA $\sim 186 \text{ mas}$ ($\sim 2.7 \lambda/D$ @ $\lambda = 500 \text{ nm}$)
- Contrast $< 10^{-9}$ ($15\% \Delta\lambda$)
- Throughput $\sim 12\text{-}15\%$ (varies with shear)

• Mission Concept

- Mission Life: 3 yrs, 5 yr goal
- Orbit: Heliocentric Earth Trailing
- Spacecraft: BATC-Kepler
- Instrument: LMCO
- S/C Pointing: $1 \text{ arcsec } 3\sigma/\text{axis}$
- Pointing: $15 \text{ mas } 3\sigma/\text{axis}$

• Instrument

- OTA: 1.5 m off-axis unobscured
- Visible Nulling Coronagraph w/ X/Y Nullers
- Wavelength $450 - 850 \text{ nm}$
- OTA Wavefront Error: $\sim \lambda/20 \text{ rms}$, $\sim 1/f^3$
- Active Null Control ($\sim 1/1000 \text{ sec}$) via 2 DM's and SFA

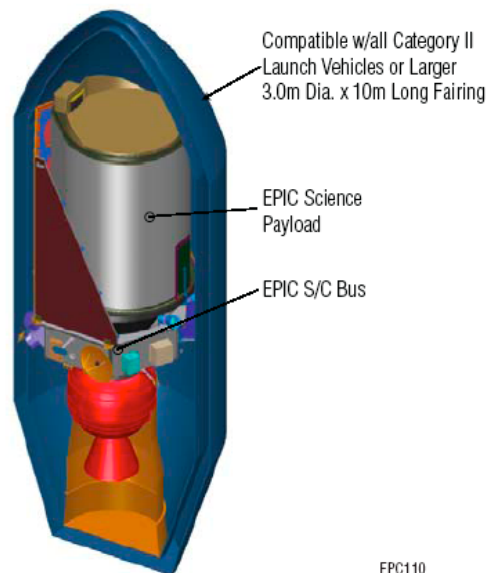
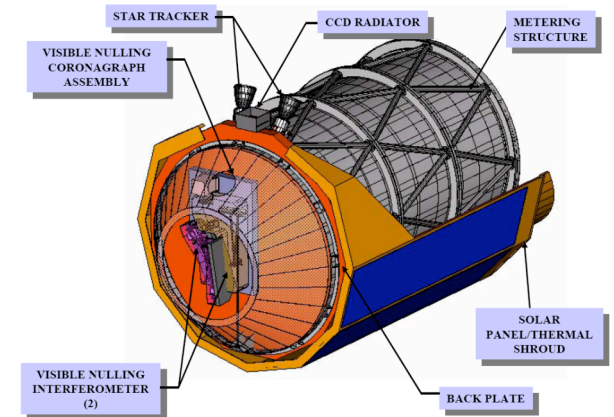
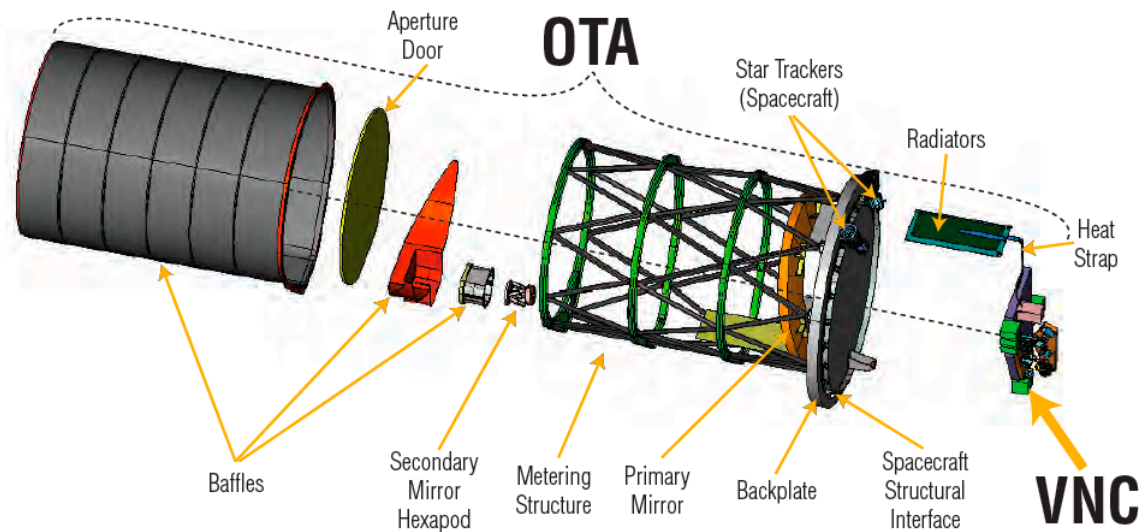


- EPIC, can characterize at least 7 known RV planets
- By launch potentially many more

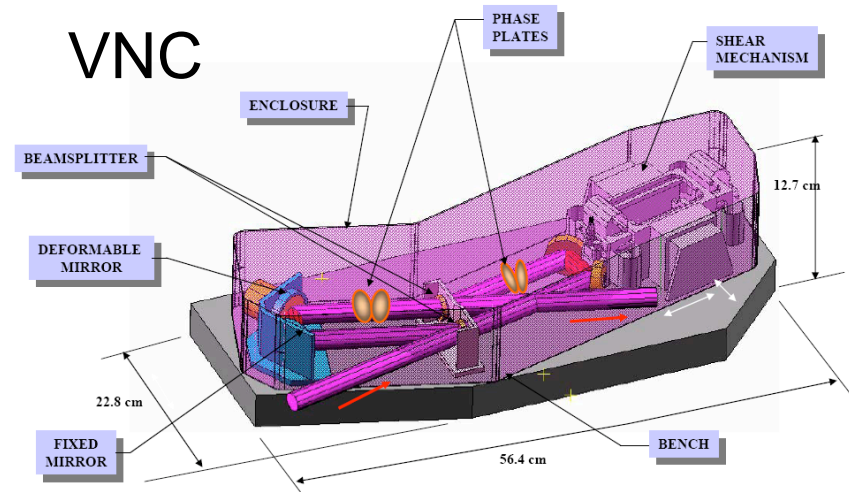


EPIC Spacecraft & Science Payload

• EPIC employs Kepler bus



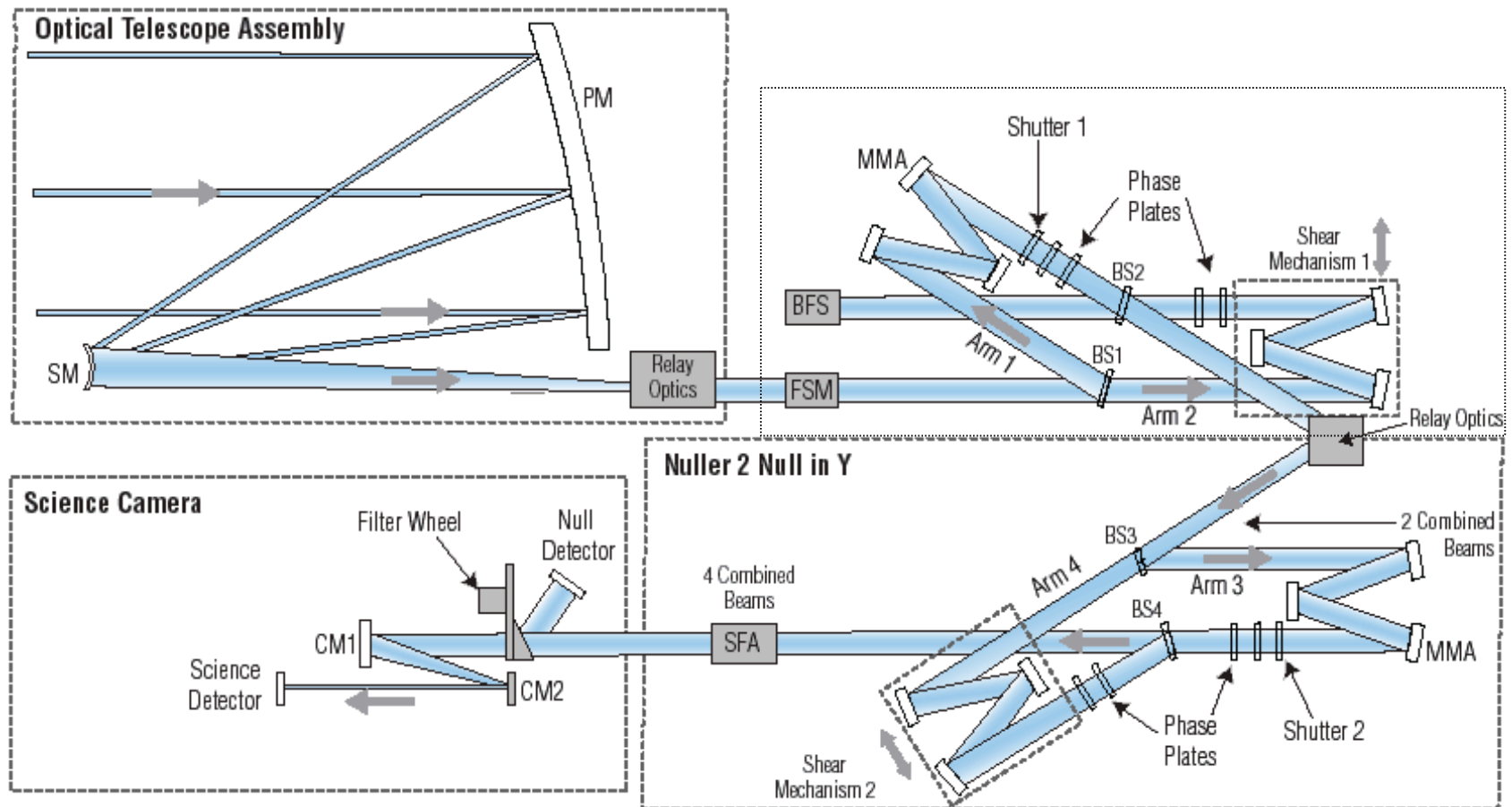
VNC





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EPIC: Schematically



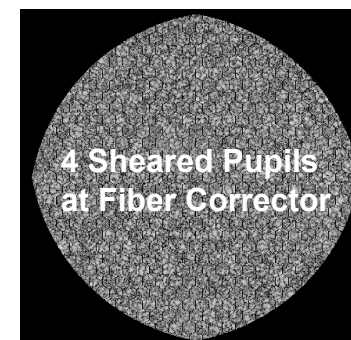
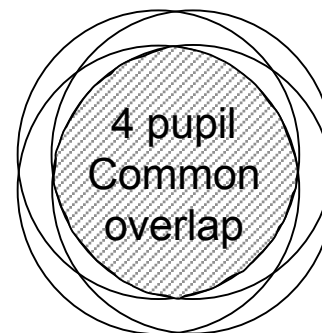
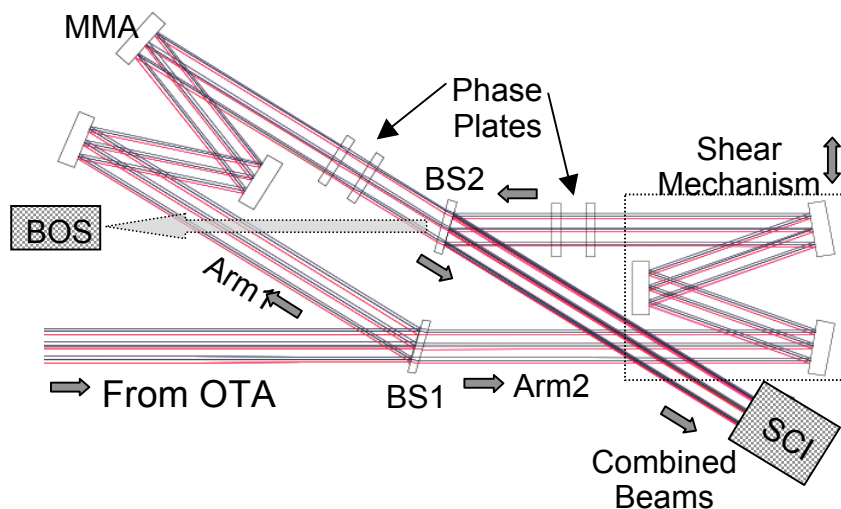
Not to scale

- modular => OTA, 2 nullers, Sci Cam



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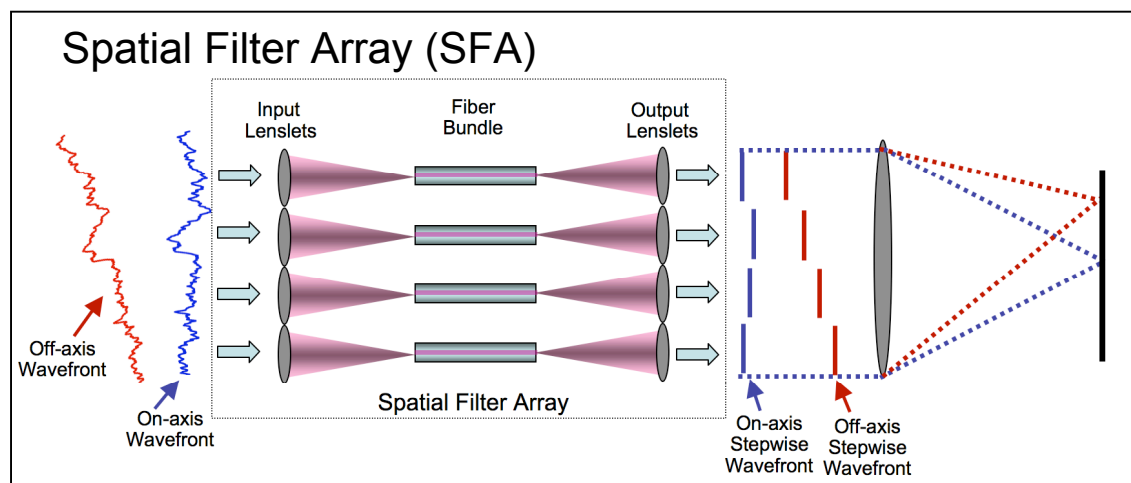
Principle of Visible Nulling Coronagraph (VNC)



- Sky transmission pattern:

$$T(\theta) = \sin^2(2\pi s_x \theta_{xp}) \sin^2(2\pi s_y \theta_{yp})$$

- Looks like \sin^2 occulter but:
 - achieved w/o focal plane mask
 - and is tunable via shear
- SFA w/DM's clean up amp/WF

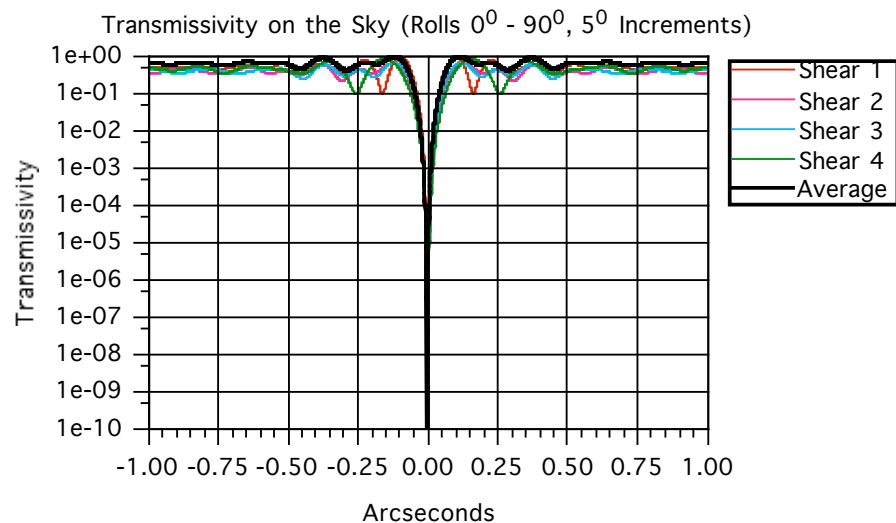




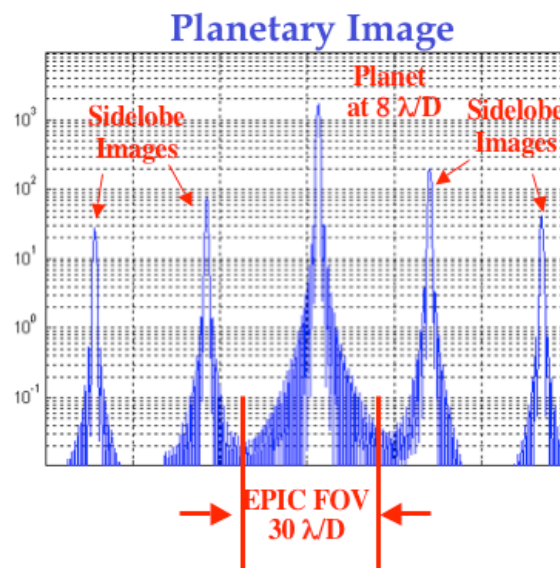
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Search Mode

Build up transmission via shear/roll



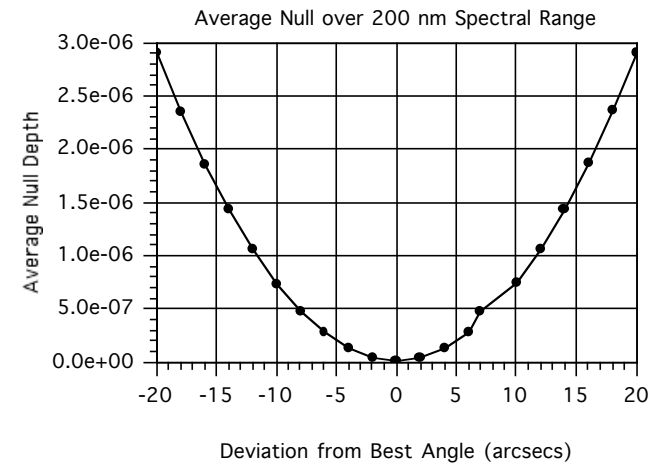
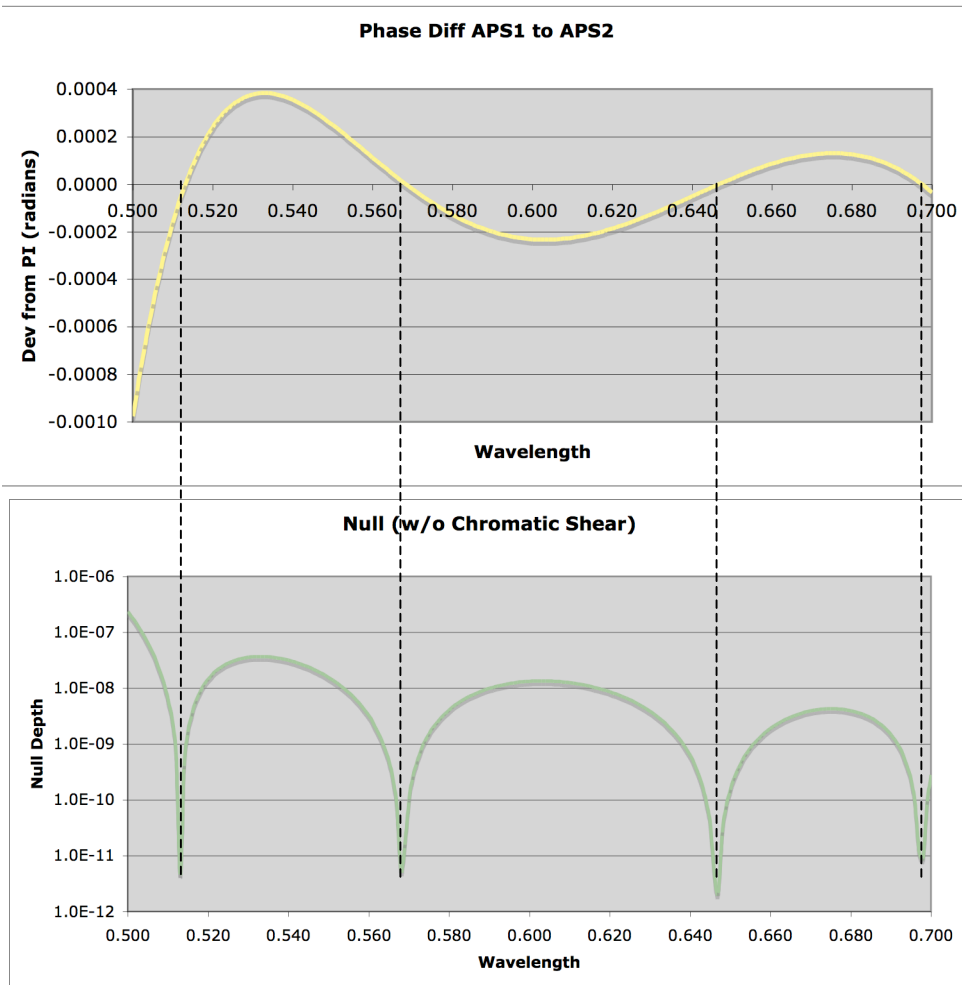
- Build up Fourier components of transmission
W/ shear, roll combinations
 - Discovery mode \Rightarrow 4 shears / 3 rolls
 - Characterization \Rightarrow 1 shear / 1 roll





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Achromatic Nulling



- 4 plates (2 per arm per nuller FS, BK7)
- Dispersion => path length deviation per λ
- Function of thickness, angle, $n(\lambda)$
- Solve via using simulated annealing
- 4 zero crossings => 4 deep nulls
- Null depth < 10^{-7} over range e.g. 0.5 - 0.7
- Sensitivity: $\sigma \sim \pm 2$ arcsec/glass
- Can be done with gratings / grism also...

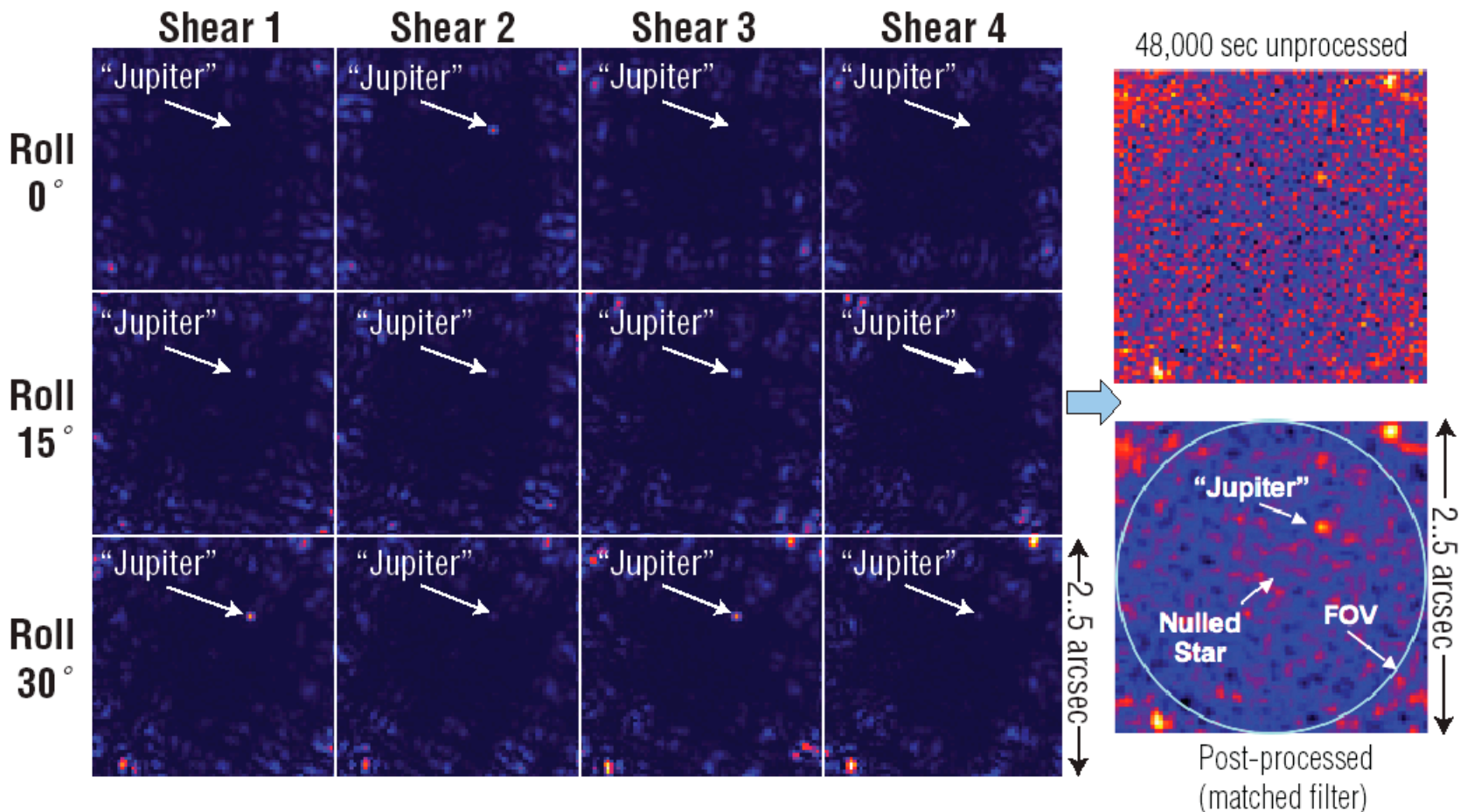


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EPIC *Discovery Mode* (Simulations)



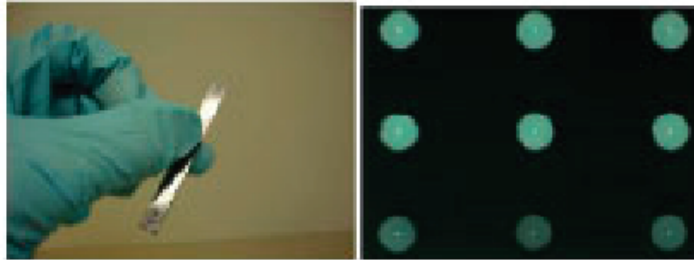
- While searching for planet (Discovery mode)
- 12 separate (3 rolls/4 shears) 4,000 sec exposures
- Null Control every 1,000 secs
- 560 +/- 42 nm filter



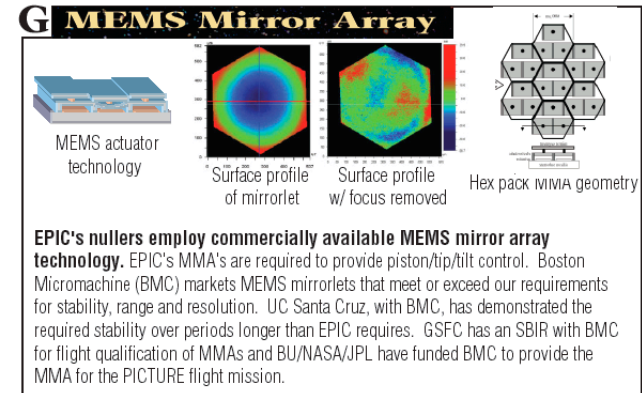
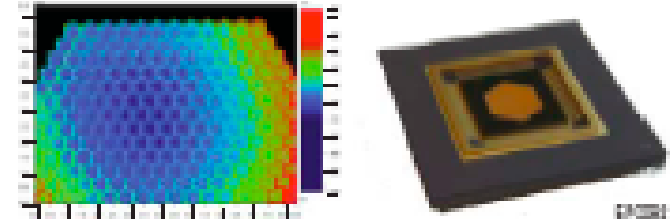


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Technologies



EPIC's spatial filter array consists of a compact fiber bundle (left) composed of light isolated fibers (right) sandwiched between two lenslet arrays. Col J. Ge has fabricated spatial filter arrays exceeding EPIC's required tolerances.

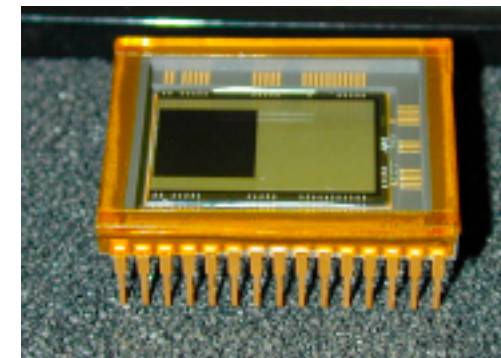


Technologies:

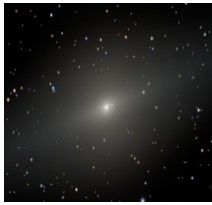
- 1.5 OTA ($\lambda/20$ rms)
- 1 - Fine steering mirror
- 2 - Matched sets of BS
- 2 - Discrete DMs (~1200 mirrorlets)
- 4 - pair Achromatic phase plates (glass/grating)
- 2 - Precision/Stable mechanisms
- 1 - Spatial Filter Array (SFA) (~1200 fibers/lenslets)
- 1 - Photon counting detector
- Null control (~1/1000 sec)

Risk associated with technologies acting in concert

Development of "large" discrete DM's (BMC/Iris-AO: SBIR's)



Photon counting CCD's



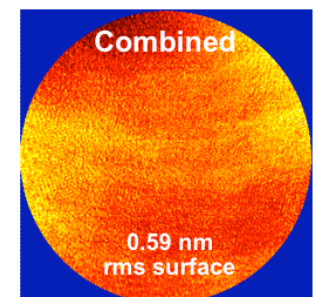
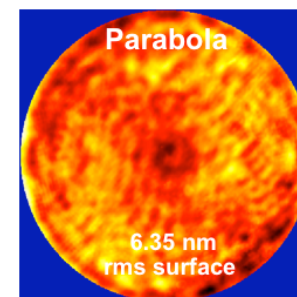
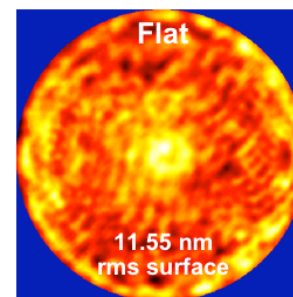
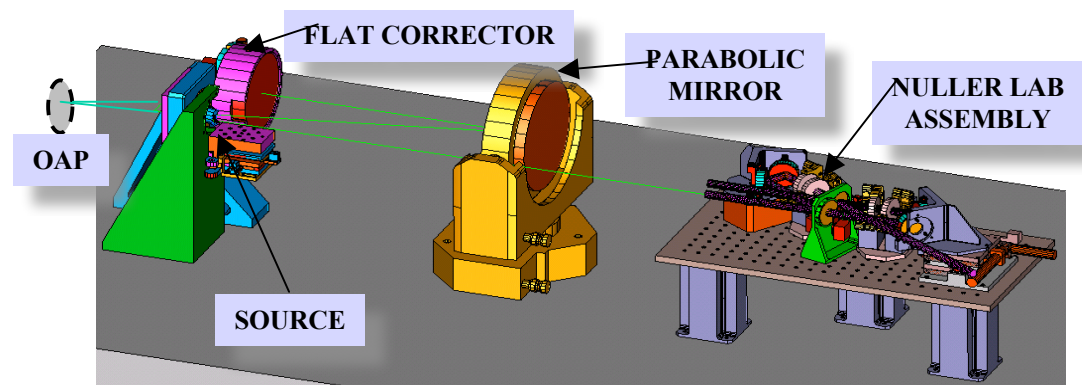
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GSFC: Visible Nulling Coronagraph Testbed



3 Main Assemblies:

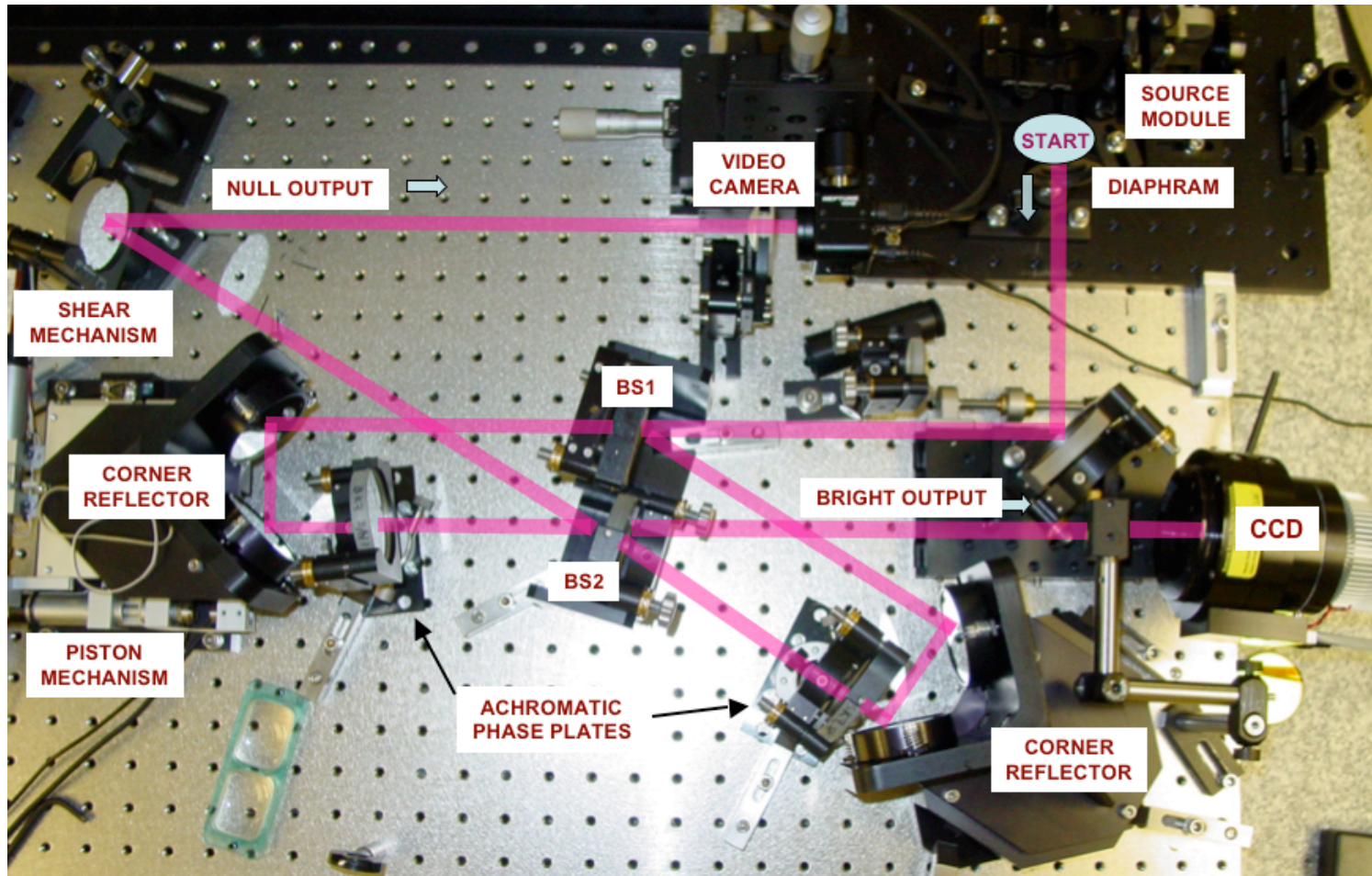
- (1) Telescope Emulator (ASML optics)
Control WFE from $\lambda/424$ to $\lambda/20$ rms
Fiber source, pellicle BS, OAP, Flat...
- (2) Visible Nulling Coronagraph (LMCO)
2 BS, 4 achromatic plates, actuators,
HeNe, Diode Laser, White light fiber source,
HOE, CCD, theodolites, CMM, Davidson
- (3) Fiber bundle test fixture
BS, Fiber Bundle, Deformable Mirror, CCD





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GSFC Lab Breadboard





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Lab Results to Date



- Observed null to $\sim 1.4 \times 10^{-4}$ (white light in air)
- Theoretical contrast $\sim 1.4 \times 10^{-7}$ (inferred)
- Null's not yet stable (vibration/turbulence)
- Thermal source
- Likely better with spectral filter(s)
- Super continuum source ordered
- Currently concentrating on stabilization
- Vacuum tank delivered

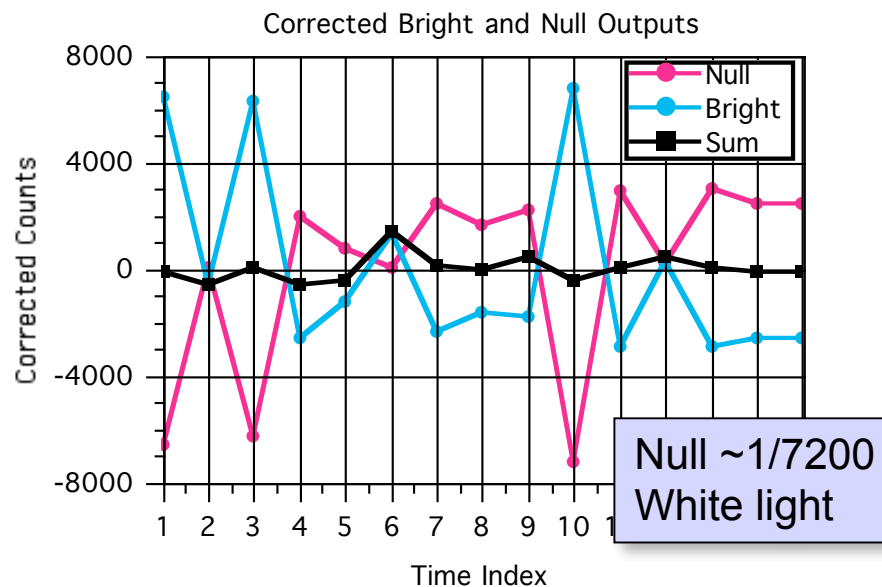
- *Dancing fringes* due to acoustics/vibration
- Moved from clean room to more stable lab
- Bright / Null fringes show correct out of phase behavior & achromaticity
- Null is time averaged due to frame time, & dancing fringes
slow frame rate for CCD $\sim 1/2$ sec

VNC Lab White Light Images



Bright Channel

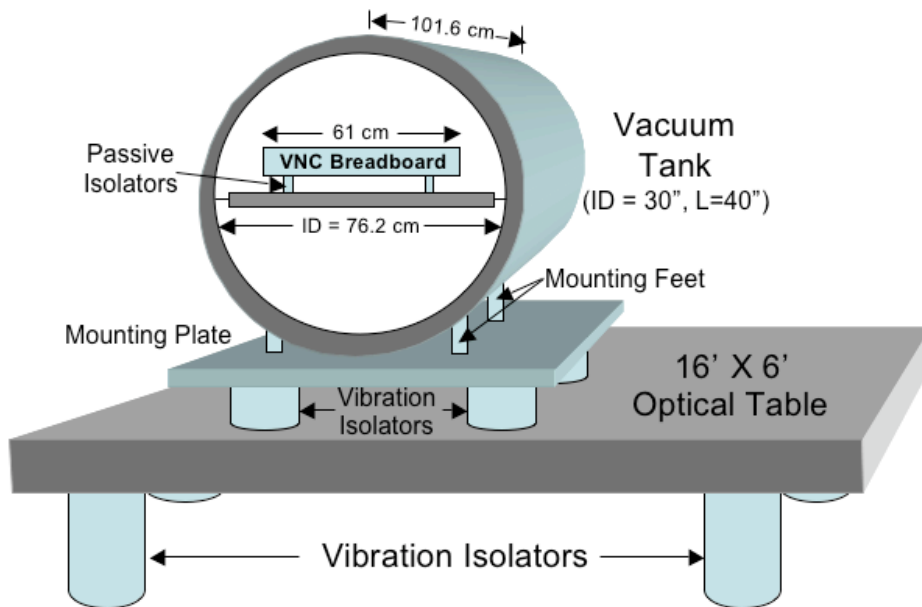
Null Channel





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Heading towards Vacuum



- Custom vacuum tank procured
- 3 DM's procured
- 10 x 10 fiber bundle w/ lenslet arrays procured
- DM with fiber to be tested on separate small Michelson



EPIC Discussion/Conclusions



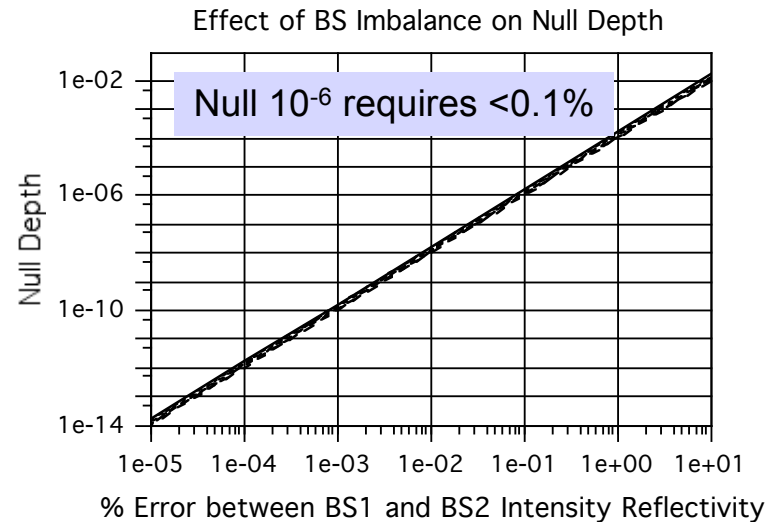
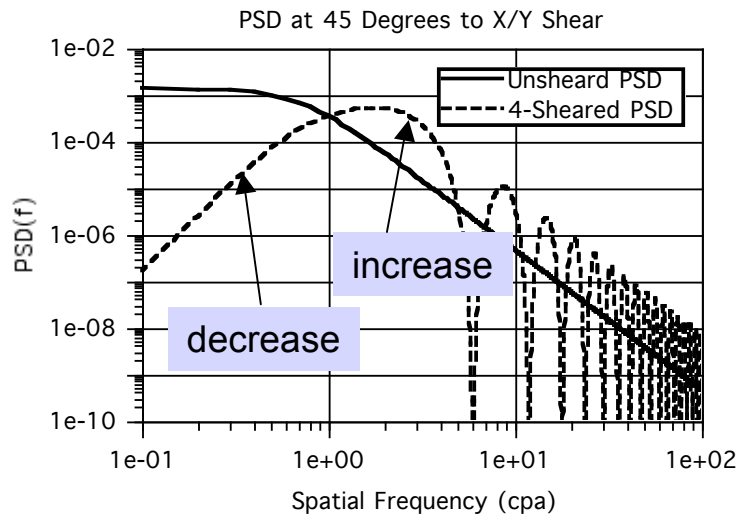
- IWA => EPIC $\sim 2.7 \lambda/D$ (186 mas), sensitivity to resolved source > 10 mas ($0.05 \lambda/D$)
- Null Control:
 - No intermediary WF/Amp sensed
 - Sense only that which is important => Null
 - Pupil plane sensing => parallel / multiplexed
 - Can be performed rapidly after initial control step
- No optics at or near focal planes
 - Doesn't suffer from mask tolerance problems
 - nor mask chromaticity
- For Jovian planet detections most components meet requirements
 - except # of DM / fibers => MEMS is inherently scalable
 - BMC & IRIS-AO have NASA/SBIRs
 - SFA technology growing
- Lab can validate models & increase null control algorithm fidelity
- VNC Allows obscurations, segmented or sparse aperture
- Expandable to > 2 m apertures (will look at Terrestrial detections w/2m & tighter IWA)
- Chromatic effects
 - chromatic tilt due to tip/tilt DM correction of grey reflectivities => drives OTA amp nonuniform
 - residual leakage of achromatic phase plates
- Observational efficiency requires:
 - repointing, spectral retuning (rotate phase plates), null control
- Throughput varies with shear and wavelength, average $\sim 15\%$
- GSFC lab level demo with DM/fiber bundle/null control in progress
- Need direct contrast measurement, currently requires level of inference from null to contrast
- Also contrast is planet to residual star => need planet simulator in lab (as do others).
- JPL (M.Shao/M. Levine) have achieved deep nulls $\sim 10^{-6} \Rightarrow 10^{-9}$ contrast
- Much interest in nulling for TPF-I, Keck etc...



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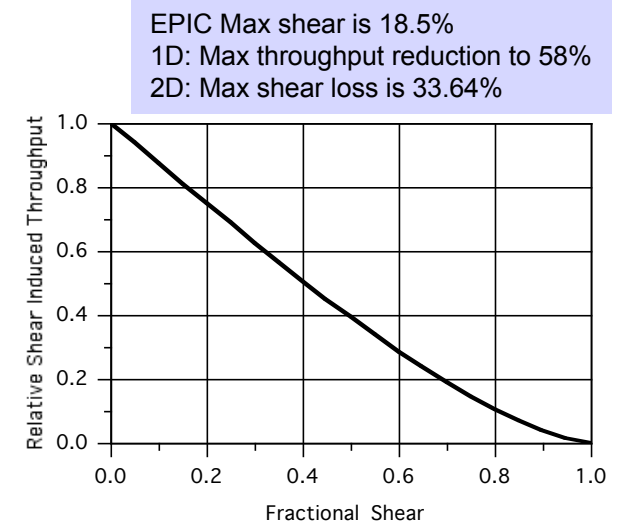
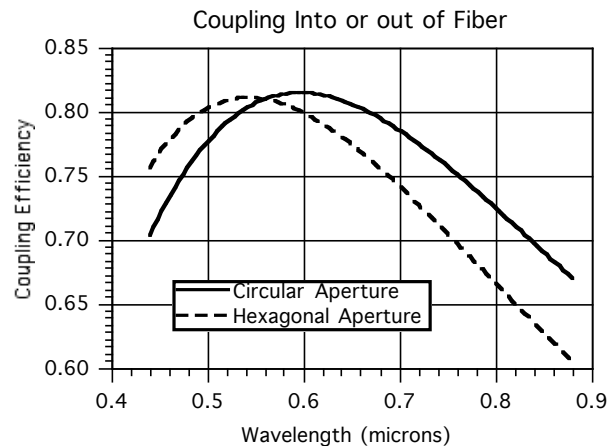
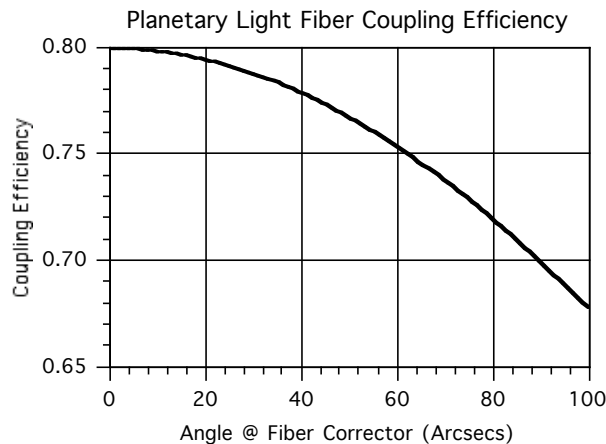
Backup Slides



Open Loop: Shear decreases low cpa sensitivity
Increases mid cpa freq sensitivity

Closed Loop: segmented DM w/SFA corrects to N/2 cpa

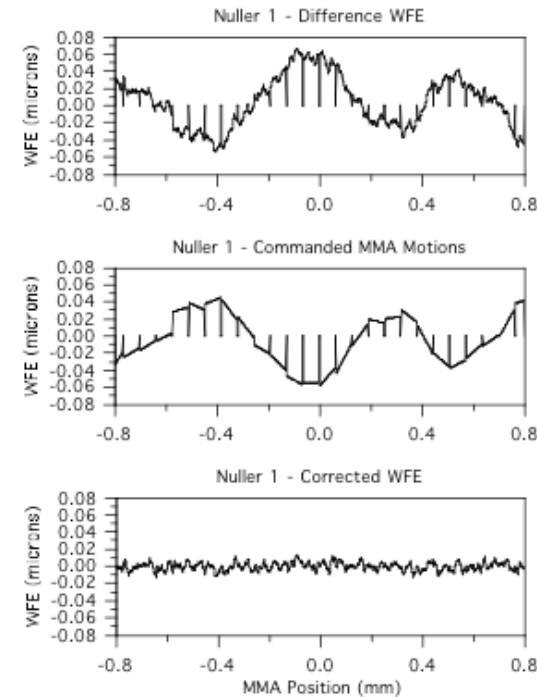
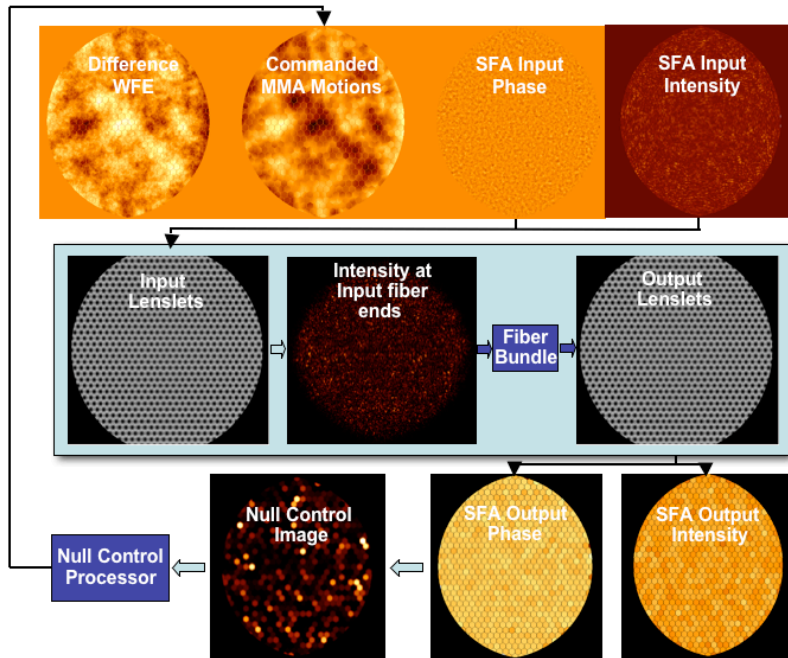
Drift/null control step: sets requirements





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Null Control



- SFA pupil image to photon counting detector
- Multiplex null control (implicit WF & Amp)
- Each sub-Ap independently (~1200 subAps)
- Assume full bright flux:
 - $V=5$, $A = 1.77 \text{ m}^2$, $\lambda = 500 - 575 \text{ nm}$, $T = 12\%$
 - Rate ~ 13275 photons/sec/subaperture
- Reduce null from 1.0 to $<10^{-7}$ with gain/step ~0.1

$$N_f = \text{Null} \cdot N_0 = g^{n\text{Step}} N_0 \Rightarrow n\text{Step} = 7$$

$$\text{such that final SNR} = 5 \quad \sqrt{N_f} = \sqrt{g^{n\text{Step}} N_0} = \text{SNR}_f \quad N_0 = R \Delta t_{\text{step}}$$

$$\Delta t_{\text{Total}} = \frac{n\text{Step} \cdot \text{SNR}_f^2}{g^{n\text{Step}} R} = 131826 \text{ sec (37 hrs)}$$

Initial null control
Worst case:

Closed Loop:

- drift from 10^{-7} to 10^{-6} null
- bring back down to 10^{-7}
- retune for each shear/roll
- retune for each filter

$$\Delta t_{\text{step}} = \frac{\text{SNR}_f^2}{g^1 R} = 0.019 \text{ sec}$$